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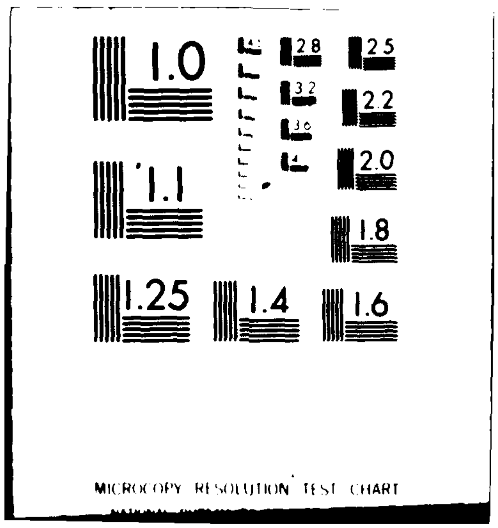
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RADC-TR-82-7
In-House Report
January 1982

(12)

TROPOSPHERIC REFRACTION CORRECTIONS USING EXOATMOSPHERIC SOURCES

Edward E. Altshuler
Koichi Mano

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The performance of radar and navigation systems that operate at low elevation angles is often limited by tropospheric refraction, which produces two main effects on radio waves, angular bending and range error. These errors increase with decreasing elevation angle and are of the order of 0.7° and 100 m respectively near the horizon. For some locations, and for many applications, antenna pointing corrections based on surface refractivity are adequate for elevation angles above a few degrees. However, new systems which operate at elevation angles near the horizon require improved accuracies.

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20. Abstract (Continued)

A technique for obtaining angle and range error corrections by utilizing exo-atmospheric calibration sources, such as radio sources or satellites, has been reported. In this report, a sensitivity analysis of this technique established the accuracies possible for angle and range error corrections. Three types of errors limit the accuracy of these corrections: measurement errors, computational errors, and errors in estimating distances. The parameters to be measured are the apparent elevation angle of the calibration source and the surface index of refraction. One integral must be evaluated numerically to calculate the range error. Finally, the radius of the earth, the heights of the target and calibration source, and a residual range error that arises because the calibration source cannot be tracked to zenith must be estimated.

A detailed analysis of the effect of uncertainties in the measured parameters on the accuracies of the angle and range error corrections was conducted assuming all errors to be independent. All calculations were based on a 1958 refractivity profile compiled by the Central Radio Propagation Laboratory of the National Bureau of Standards. It was found that the refraction corrections were most sensitive to errors in the apparent elevation angle of the calibration source and only moderately sensitive to variations in the surface refractivity. Other sources of error have only a slight effect on the correction accuracies. We conclude from this study that accuracies within approximately 2-3 percent of the total correction are possible.

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1. INTRODUCTION

The performance of radar and navigation systems that operate at low elevation angles is often limited by tropospheric refraction, which produces two main effects on radio waves, angular bending and time delay. The angular bending is due to the change of the index of refraction with the height of the atmosphere. The time delay occurs primarily because the index of refraction is greater than unity, thus slowing down the wave, and to a lesser extent, because of the lengthening of the path by angular bending. Since radar and navigation systems determine range from time delay measurements, the additional time delay produced by the troposphere results in a corresponding range error. For illustration, in Figure 1, the refractive angle and range errors are plotted as a function of elevation angle for a CRPL Reference Atmosphere (see Figure 2). Since the angle error of a source is also a function of altitude, cases are shown for altitudes of 90 km, for which the index of refraction is approaching unity, and infinity, which would correspond to a celestial radio source. It is seen that these errors increase with decreasing elevation angle and are the order of 0.7° and 100 m respectively near the horizon.

For some locations, and for many applications, antenna pointing corrections based on surface refractivity alone or, if necessary, on a vertical refractivity

(Received for publication 18 January 1982)

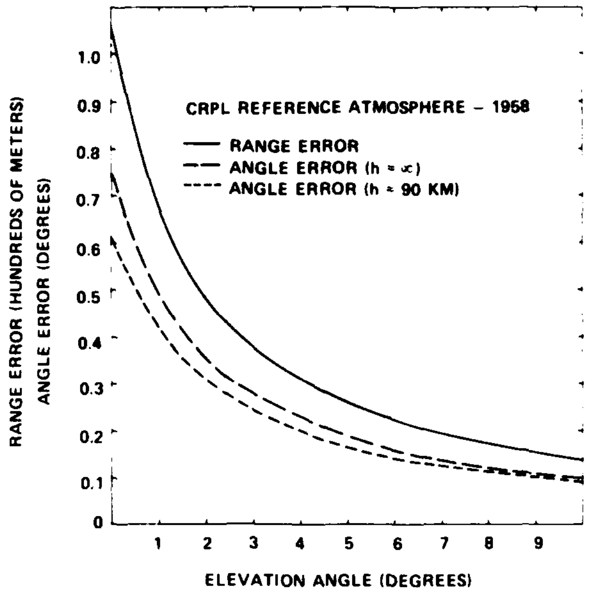

Figure 1. Typical Tropospheric Refraction Angle and Range Errors

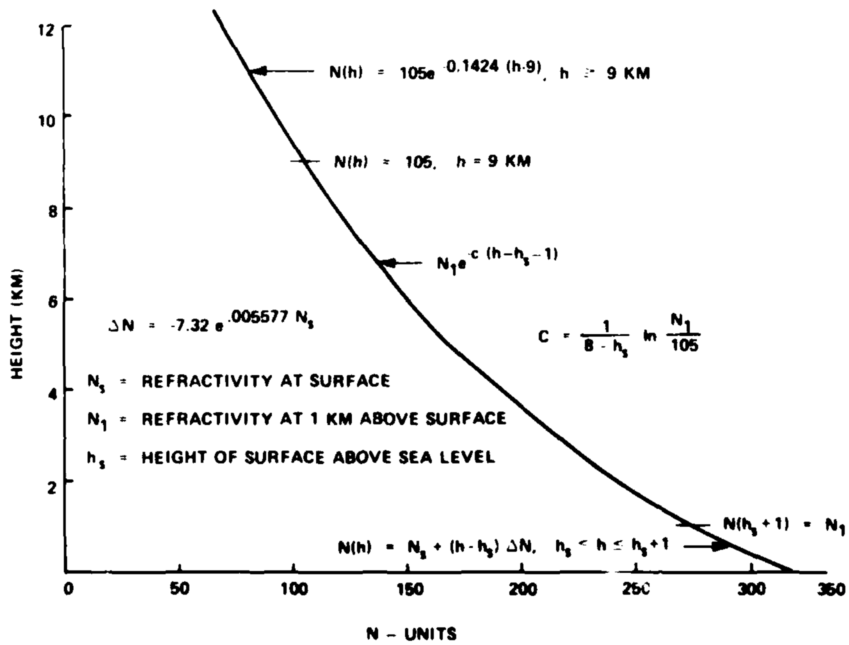

Figure 2. CRPL Reference Atmosphere – 1958

profile are adequate for elevation angles above a few degrees.[1] However, new systems that operate at very low elevation angles require improved accuracies.

A technique for obtaining angle and range error corrections by utilizing exo-atmospheric calibration sources (often referred to as "targets of opportunity") such as the limb of the sun, radio sources or satellites has been reported. The angle error correction for a target can be determined from an angle error measurement of a calibration source if the approximate heights of the calibration source and target are known. However, neither radio sources nor satellites are suitable for range calibration, since radio sources are detected passively and the true range of a satellite is not generally known to a sufficient enough accuracy to be of value. Mano and Altshuler[2] have shown however, that the range error can be expressed as a function of angle error data thus making it possible to obtain range error corrections from a set of angle error measurements.

Three types of errors limit the accuracy of this technique, measurement errors, computational errors, and errors in estimating distances. The parameters to be measured are the apparent elevation angle of the calibration source and the surface index of refraction. One integral must be evaluated numerically to calculate the range error. Finally, the radius of the earth, the heights of the target and calibration source above the earth, and a residual range error that arises because the calibration source cannot be tracked to zenith must be estimated.

In this report, a sensitivity analysis of this technique determines how these errors affect the accuracy with which angle and range error corrections for the target can be obtained. To solve this problem, we assume a time independent, spherically stratified, nonionized atmosphere with an index of refraction that monotonically decreases with increasing altitude. As a result, our solution is only valid at frequencies above which ionospheric effects are negligible and cannot be applied to atmospheres having inversion layers in refractivity. Also, it is assumed that both the calibration source and the target, the position of which is to be determined, are at heights above which the refractivity is negligible, that is, above the troposphere.

2. ANGLE ERROR CORRECTION

Consider a radio wave traversing a medium for which the atmospheric index of refraction is a function of the radial distance r from the center of the earth;

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1. Bean, B.R., and Dutton, E.J. (1966) Radio Meteorology, Nat. Bur. Stand. Monograph 92, U.S. Government Printing Office, Washington, D.C.
2. Mano, K., and Altshuler, E.E. (1981) Tropospheric refractive angle and range error corrections utilizing exoatmospheric sources, Radio Science 16(No. 2):191-195.

$n = n(r)$. The ray path lies in the great circle plane determined by the locations of the antenna and target, as shown in Figure 3 and is described by Snell's law,

$$r\, n(r) \cos\theta(r) = \text{const.} \tag{1}$$

Here $\theta(r)$ represents the elevation angle of the tangent to the ray at a point of radial distance r. The antenna is assumed to be located on the earth's surface, at a distance a from its center. We designate the positions of the target and calibration sources as 1 and 2, respectively, and the parameters relevant to each are labeled with the corresponding subscripts. Thus r_1 and r_2 are the distances from the earth's center, h_1 and h_2 are the heights above the earth, and ε_1 and ε_2 are the angle errors for the target and calibration source respectively. The angle error ε_2 of the calibration source is determined as follows. The apparent elevation angle of the source, θ_a, is measured and the precise time is recorded. The true angular position of the source, θ_t, is determined, at that time, from ephemeris data. The angle error of the source is then

$$\varepsilon_2(\theta) = \theta_a - \theta_t \,. \tag{2}$$

Before the angle error ε_1 for that target can be computed it is necessary to first calculate the angular refraction, τ. It has been shown that[2]

$$\tau = \frac{\pi}{2} + \varepsilon_2 - \cos^{-1}\left[\frac{a}{a+h_2}\; n(a)\cos\theta_a\right] - \sin^{-1}\left[\frac{a}{a+h_2}\;\cos(\theta_a - \varepsilon_2)\right] \tag{3}$$

where n(a) is the surface index of refraction. It is interesting to note that as h_2 approaches infinity, ε_2 approaches τ. Therefore, for celestial calibration sources, τ is approximately equal to ε_2. If both the target and calibration source are assumed to be outside the troposphere, where the index of refraction is approximately unity, then the angular refraction is the same for both, given that they have the same initial elevation angle. If the target is below the troposphere, then its angular bending is slightly less than that of the calibration source and this difference must be estimated, based on the height of the target. With τ known, the angle error of the target, ε_1, can now be determined from

$$\begin{aligned}\sin(\tau-\varepsilon_1)&\left[\sqrt{(a+h_1)^2 - a^2\cos^2(\theta_a-\varepsilon_1)} - a\sin(\theta_a-\varepsilon_1)\right]\\ &= \sin(\tau-\varepsilon_2)\left[\sqrt{(a+h_2)^2 - a^2\cos^2(\theta_a-\varepsilon_2)} - a\sin(\theta_a-\varepsilon_2)\right]\end{aligned} \tag{4}$$

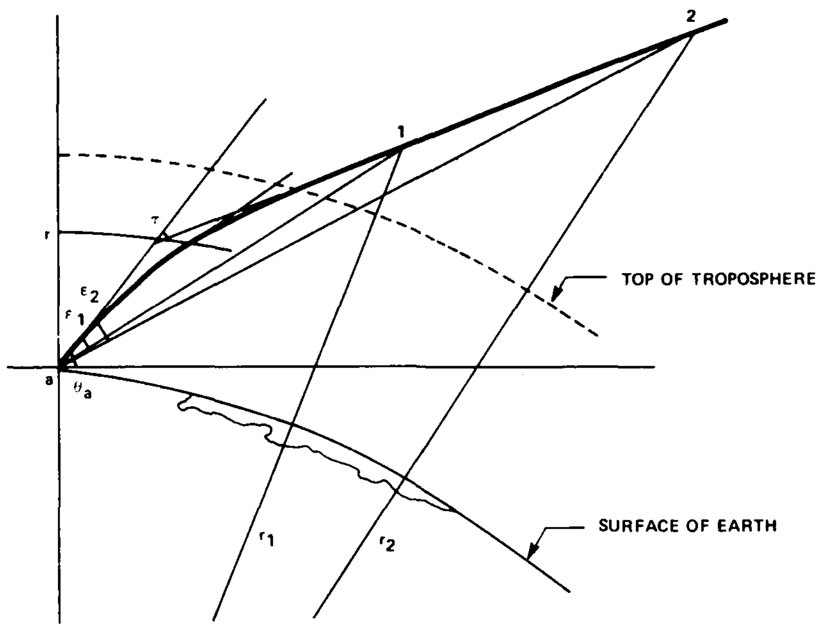

Figure 3. Geometry of the Problem

As mentioned previously there are several types of errors that limit the accuracy to which the angle and range error correction can be determined. In Eq. (4) we assume that the target height, h_1, is 90 km, the calibration source is celestial ($h_2 = \infty$); the earth radius a is 6370 km and the index of refraction is that of a CRPL Reference Atmosphere with n(a) equal to 1.000313. We then proceed to conduct a sensitivity analysis of ε_1 on the above parameters by varying each; it is assumed that the uncertainties in the parameters are statistically independent because of the nature in which they are obtained. The errors in the angular position of the target, based on these uncertainties, are plotted in Figure 4 as a function of elevation angle. These data can be linearly extrapolated to smaller or larger changes in refractivity or distances. Also, it is expected that the general characteristics of these curves will not change significantly for different heights of the target or calibration source. It is seen that earth radius and target height accuracies of about ± 1 km are needed to achieve angular accuracies which are a fraction of a millidegree (mdeg). Surface refractivity must be measured to an accuracy of better than one N-unit to achieve a comparable accuracy, particularly for the very low elevation angles.

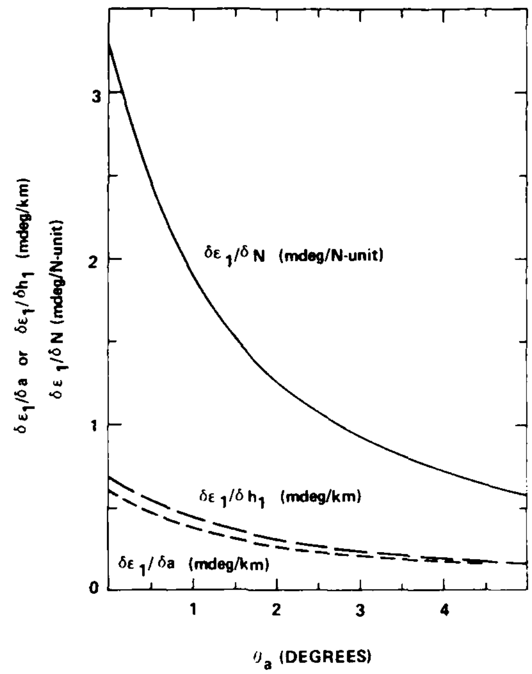

Figure 4. Dependence of Angle Error Correction on Surface Refractivity, Earth Radius, and Target Height

To examine the dependence of ε_1 on the measurement accuracy of ε_2, we take the derivative of Eq. (4)

$$\delta\varepsilon_1 = \left\{ 1 + \frac{\dfrac{a\,n(a)\sin\theta_a}{\sqrt{(a+h_1)^2 - (a\,n(a)\cos\theta_a)^2}} - \dfrac{a\,n(a)\sin\theta_a}{\sqrt{(a+h_2)^2 - (a\,n(a)\cos\theta_a)^2}}}{1 - \dfrac{a\sin(\theta_a - \varepsilon_1)}{\sqrt{(a+h_1)^2 - \left[a\cos(\theta_a - \varepsilon_1)\right]^2}}} \right\} \delta\varepsilon_2 \tag{5}$$

The ratio of the angular errors of the target, for different heights, to those of the calibration source are plotted in Figure 5, where once again the calibration source is assumed to be at infinity. It is seen that the angular accuracy with which the target can be located improves as its apparent elevation angle becomes smaller and its height increases. This is just the opposite of the behavior of the other errors, which is fortunate since they are all statistically independent. The angle

error accuracies of the target are shown in Table 1 as a function of all of the parameters previously discussed. In addition, rms accuracies for these statistically

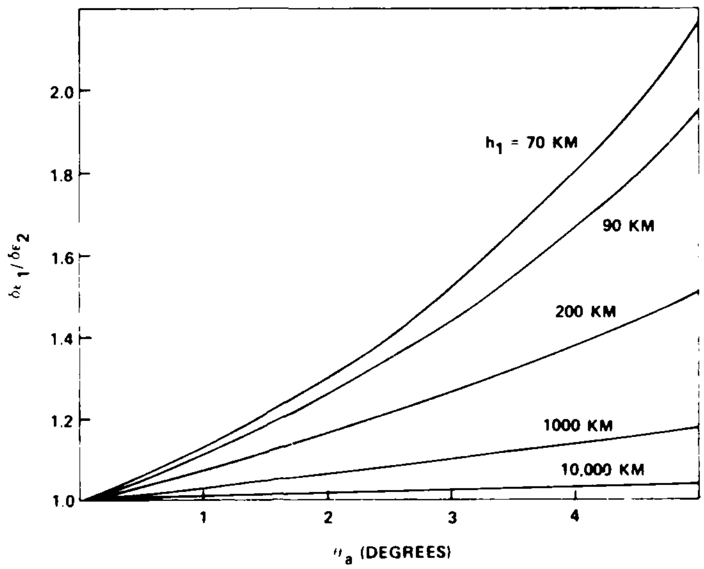

Figure 5. Dependence of Angle Error Correction on Apparent Elevation Angle of Calibration Source

Table 1. Dependence of Angle Error Correction on: Accuracy of Apparent Elevation Angle of Calibration Source, Surface Refractivity, Earth Radius, and Target Height*

θ_a	$\delta\epsilon_1/\delta\epsilon_2$	$\delta\epsilon_1/\delta N$	$\delta\epsilon_1/\delta a$	$\delta\epsilon_1/\delta h_1$	rms** mdeg
deg		mdeg/N-unit	mdeg/km	mdeg/km	mdeg/km-N-units
0	1.00	3.30	0.61	0.68	3.57
1	1.11	1.90	0.41	0.44	2.38
2	1.25	1.27	0.31	0.32	1.84
3	1.43	0.94	0.24	0.25	1.75
4	1.66	0.73	0.20	0.20	1.75
5	1.94	0.60	0.16	0.17	2.04

*For a surface refractivity of 313 N-units, earth radius of 6370 km and target height of 90 km.

**Assume errors of ± 1 mdeg for angle of calibration source, ± 1 N-unit for surface refractivity and ± 1 km in earth radius and target height respectively. Calibration source is assumed to be at infinity.

independent errors are also tabulated but since the parameters have different units it is necessary to fix some of them to make a comparison. Thus it is assumed that the angular accuracy of the location of the calibration source is ± 1 mdeg, the accuracy of the surface refractivity N_a is 313 ± 1 N-unit, the target is at an altitude of 90 ± 1 km and the earth radius is 6370 ± 1 km. It is seen that under these conditions the angular position of the target can be estimated to about ± 2 mdeg.

3. RANGE ERROR CORRECTION

An expression for the range error has been previously derived[2] and is shown in Eq. (6)

$$\Delta R_e \Big|_{\theta=\theta_m}^{\theta=\theta_a} = \left[\left(\sqrt{[r\,n(r)]^2 - [a\,n(a)\cos\theta]^2} - \sqrt{r^2 - \{a\cos[\theta - \epsilon(\theta)]\}^2}\right)\Big|_{r=a}^{r=r_1} + a\,n(a)\cos\theta\,\tau(\theta)\right]\Big|_{\theta=\theta_m}^{\theta=\theta_a} - a\,n(a)\int_{\cos\theta_m}^{\cos\theta_a} \tau(\theta)\,d\cos\theta \tag{6}$$

where

$\tau(\theta) = \frac{\pi}{2} + \epsilon(\theta) - \cos^{-1}\left(\frac{a}{r_1}\,n(a)\cos\theta\right) - \sin^{-1}\frac{a}{r_1}\cos[\theta - \epsilon(\theta)]$

$n(r)$ = index of refraction at point r.

θ_a = apparent elevation angle for which range error correction is calculated.

θ_m = maximum elevation angle of calibration source.

As mentioned before, there are several sources of error that limit the accuracy to which the range error correction can be determined. In Eq. (6) we assume that the target height h_1 is 90 km; the calibration source is celestial, $h_2 = \infty$; the earth radius a is 6370 km; and the index of refraction is that of a CRPL Reference Atmosphere with a surface value of 1.000313. For illustration, we further assume that we are interested in obtaining a range error correction for a target at an elevation angle of $\theta_a = 3^{\circ}$ and that the maximum angle at which we can measure the apparent elevation angle of the calibration source is $\theta_m = 20^{\circ}$.

We shall first examine the computational accuracy of the integral in Eq. (6). An extended form of Simpson's rule having the format shown in Eq. (7) was used.

$$\int_{\cos\theta_m}^{\cos\theta_a} \cos\theta \ d\cos\theta = \sum_{i=1}^{6} \frac{1}{12}(\tau_{i1} + 4\tau_{i2} + 2\tau_{i3} + 4\tau_{i4} + \tau_{i5}) \cdot (\cos\theta_{i5} - \cos\theta_{i1}) \tag{7}$$

where

$$\tau_{ij} = \tau(\cos\theta_{ij}).$$

In practice, a set of elevation angles, θ_{ij}, falling in the interval between θ_m and θ_a is selected using an algorithm which weights the distribution of angles in an optimal manner. The accuracy with which the integral can be evaluated increases with the number of angles used and in Figure 6 the numerical integration is shown as a function of the number of angles for $\theta_a = 3^o$. The true value of the integral is 551.92 m. It was found that an error of less than 0.1 percent (~0.5 m) could be achieved if 25 angles were used. In Figure 7 the number of angles that would be needed to obtain a comparable accuracy for other elevation angles is plotted. It is seen that as the elevation angle for which the correction is desired decreases, more angles are needed; over 50 angle error measurements are required for targets approaching the horizon.

The apparent angular positions of the calibration source are measured at these angles and the corresponding values of τ are calculated from Eq. (3).

For illustration, the actual distribution of angles used in Eq. (7) are tabulated in Table 2 for $\theta_m = 19.5^o$, $\theta_a = 3^o$, and n = 25. It should be noted that although there are 30 angles tabulated, 5 angles in the first and last columns are the same, so the measurements are only made at 25 angles. Also, note that the angles are not uniformly distributed but rather are weighted toward the lower angles.

We then proceeded to conduct a sensitivity analysis of ΔR_e on variations in h_1, a, N_a, and ε_2 assuming that errors in measuring or estimating these parameters are statistically independent. We found that the dependence of ΔR_e on the accuracy of either h_1 or a is very weak with changes only of the order of millimeters in ΔR_e for errors of the order of kilometers in either h_1 or a. The effect of an error in N_a on ΔR_e was significant and is plotted in Figure 8. It is seen that an error of one N-unit can result in an error of several tenths of a meter at very low elevation angles.

Next, the dependence of ΔR_e on ε_2 was studied. Eq. (6) was solved for uncertainties in ε_2 from $\pm 0.01^o$ to $\pm 0.0001^o$. As stated previously, the number of angles necessary to evaluate the integral was increased with decreasing elevation angle as shown in Figure 7, so that the error due to approximations in numerically calculating the integral was kept small. Because of minor computational complications θ_m

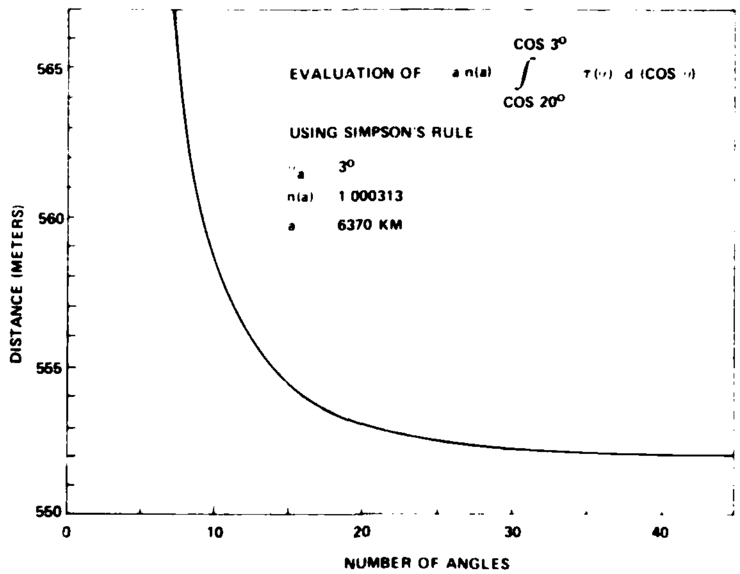

Figure 6. Computational Accuracy of Numerical Integration

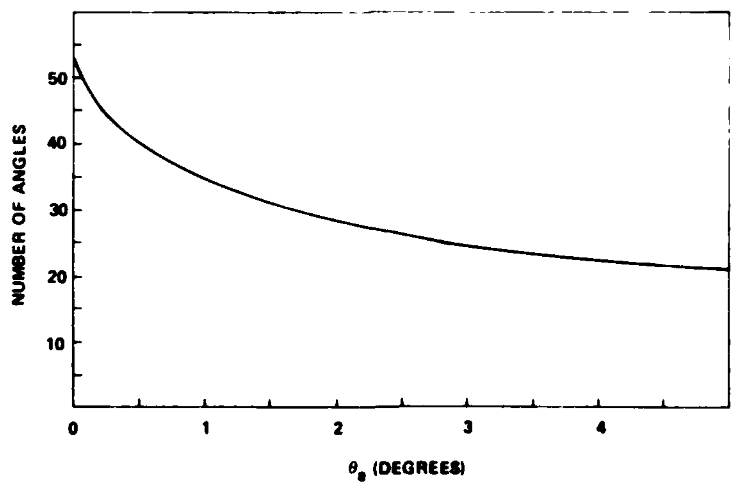

Figure 7. Number of Angles Required to Evaluate Integral with Sufficient Accuracy

Table 2. Optimum Set of Elevation Angles at which Calibration Source is Measured

i \ j	1	2	3	4	5
1	19.5000	18.2608	16.9345	15.4986	13.9193
2	13.9193	13.0598	12.1407	11.1473	10.0577
3	10.0577	9.46642	8.83611	8.15764	7.41783
4	7.41783	7.01893	6.59607	6.14431	5.65674
5	5.65674	5.39651	5.12313	4.83436	4.52725
6	4.52725	4.19778	3.84020	3.44577	3.00000

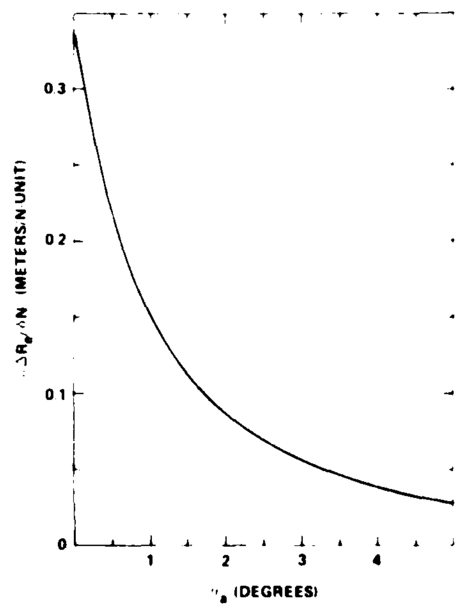

Figure 8. Dependence of Range Error Correction on Surface Refractivity

was chosen as 19.5° rather than 20°. The range error accuracy, subject to all the conditions on h_1, h_2, a, and N_a mentioned earlier, is shown in Figure 9. It is seen that accuracies in the measurement of ϵ_2 of the order of 1 mdeg are needed to obtain range error accuracies of the order of 1 m.

Finally, the residual range error that results from not being able to measure the apparent elevation angle of the calibration source at angles above θ_m was

Table 3. Approximate Range Errors (in Meters) for a CRPL Reference Atmosphere – 1958

Target Elevation θ (deg) \ Refractivity (N-units)	240	260	280	300	320	340	360	380	400
4	26.37	27.54	28.66	29.71	30.71	31.65	32.53	33.35	34.11
5	22.07	22.94	23.78	24.58	25.35	26.08	26.78	27.44	28.07
6	18.90	19.60	20.27	20.92	21.54	22.14	22.72	23.27	23.81
7	16.50	17.08	17.64	18.18	18.71	19.22	19.71	20.19	20.65
8	14.64	15.13	15.61	16.08	16.53	16.97	17.40	17.82	18.23
9	13.14	13.57	13.99	14.40	14.80	15.20	15.58	15.95	16.32
10	11.92	12.30	12.68	13.05	13.41	13.76	14.10	14.44	14.77
12	10.06	10.37	10.68	10.98	11.28	11.57	11.86	12.14	12.42
14	8.71	8.97	9.23	9.49	9.74	9.99	10.24	10.48	10.72
16	7.68	7.91	8.14	8.36	8.58	8.80	9.01	9.23	9.44
18	6.88	7.08	7.28	7.48	7.67	7.87	8.06	8.25	8.44
20	6.23	6.41	6.59	6.77	6.95	7.12	7.30	7.47	7.64
25	5.07	5.21	5.36	5.50	5.64	5.78	5.92	6.06	6.20
30	4.29	4.42	4.54	4.66	4.78	4.90	5.02	5.14	5.25
40	3.35	3.45	3.54	3.63	3.73	3.82	3.91	4.00	4.09
50	2.82	2.90	2.97	3.05	3.13	3.21	3.29	3.36	3.44
60	2.50	2.57	2.63	2.70	2.77	2.84	2.91	2.98	3.04
70	2.30	2.37	2.43	2.49	2.56	2.62	2.68	2.75	2.81
80	2.20	2.26	2.32	2.38	2.44	2.50	2.56	2.62	2.68
90	2.17	2.23	2.29	2.35	2.40	2.46	2.52	2.58	2.64

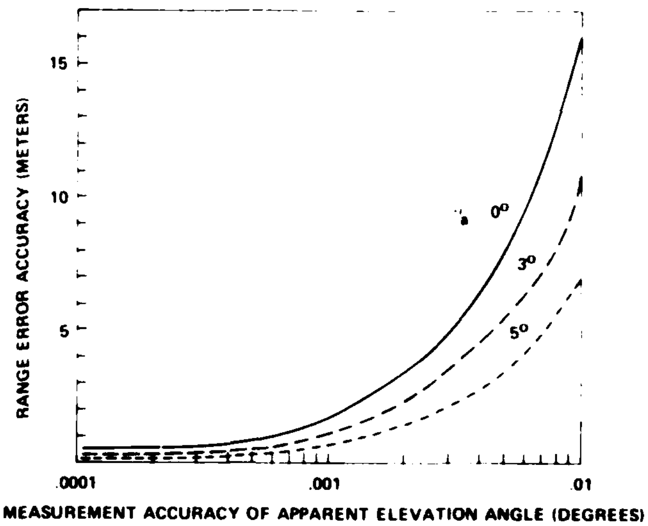

Figure 9. Accuracy of Range Error Correction

investigated. In Table 3, range errors corresponding to the CRPL Reference Atmosphere are tabulated for elevation angles from 4° to zenith for a wide range of surface refractivity.[3] It is noted that the range error drops very rapidly with increasing elevation angle and it is estimated that these values are accurate to at least 10 percent, particularly for the very high elevation angles. Thus the final step in determining a range error correction for a target at an angle of 3° would be to add on a residual correction which can be interpolated from Table 3 for N_a = 313 and θ_m = 15.5°, namely 7.06 m. Therefore, the total range error correction would be 30.65 m plus 7.06 m or 37.71 m.

4. CONCLUSIONS

A sensitivity analysis of the accuracies with which angle and range error corrections can be obtained using atmospheric calibration sources has been conducted. It has been found that both corrections are most sensitive to the accuracy with which the apparent angular position of the calibration source, ϵ_2, can be measured. For the angular error correction, the accuracy improves as the height of the calibration source decreases and that of the target increases (as their heights approach one another) as seen in Figure 5. Also, the accuracy increases as the elevation

3. Altshuler, E.E. (1971) Corrections for Tropospheric Range Error, AFCRL-TR-71-0419, AD 731 170.

angle approaches the horizon and at zero degrees the angular accuracy of the target is equal to the accuracy of the calibration source measurement. The accuracy of the range error correction on the other hand improves with increasing elevation angle, as seen in Figure 9.

The accuracies of the angle and range error corrections are only moderately influenced by the surface index of refraction measurement, however, an attempt should be made to measure the surface refractivity to an accuracy of ± 1 N-unit. The accuracies to which the earth radius and target height are estimated may slightly affect the angle error correction but are negligible regarding the range error correction.

It is difficult to estimate the impact of the residual range error that arises from the contribution from angles above θ_m. Obviously, the higher the value of θ_m, the smaller the contribution of this residual error and the less its effect on the range error correction. In summary, it seems reasonable to assume that angle and range error corrections, accurate to approximately 2-3 percent of the total correction, are possible by utilizing exoatmospheric calibration sources.

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